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ON THE OPTIMAL CHOICE OF ELECTRICAL CONDITIONING CIRCUITS FOR TRIBOELECTRIC NANOGENERATORS

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ABSTRACT

This work presents a generic procedure for the optimal choice of an unstable charge pump (UCP) circuit topology for electrostatic kinetic energy harvesters (e-KEH) biased by a triboelectric material, also known as a triboelectric nanogenerators (TENGs). Each UCP can be characterized by the ratio γ that it imposes between the maximum and minimum voltage across the transducer, in every cycle of its steady-state operation. The value of γ depends on the detailed topology of each UCP. The triboelectric transducer, on the other hand is characterized by (i) the variation ratio η between its dynamic capacitance maximum and minimum values under mechanical actuation and (ii) its DC bias V_{TE} which models the triboelectric effect. The analysis done in this paper leads to the optimal γ as a function of the transducer parameters η , V_{TE} , and as a function of the parasitic capacitance brought by the conditioning circuit or by the setup. As such, this work presents a systematic procedure to select the UCP topology maximizing the converted power for a variety of triboelectric systems. In particular, this procedure shows which of the low capacitance variation rectifier (LCVR) or of the cascade Bennet doubler rectifier (CBDR), two popular conditioning circuit topologies for e-KEH, is optimal for any given triboelectric transducer.

KEYWORDS

Triboelectric nanogenerators, electrostatic kinetic energy harvesters, unstable charge pump, low capacitance variation rectifier, cascade Bennet doubler rectifier

INTRODUCTION

Triboelectric nanogenerators (TENGs) are specific types of electromechanical transducers used for electrostatic kinetic energy harvesting (e-KEH). Over the past decade, they have emerged as a promising technology in the realm of self-powered systems, with applications ranging from healthcare to industrial monitoring. For example, TENGs can be used as tactile and pressure sensors, which can detect external mechanical stimuli without the need for external power supplies. Moreover, TENG can be built with stretchable, flexible, and biocompatible materials, making them ideal for wearable or implanted applications. Besides their usage as self-powered sensors, TENGs can also be used as

mechanical energy harvesters whose power output is used to supply a separate electronic system. In this context, TENGs can be used to convert energy from human motion, to power various biomedical applications, e.g., drug delivery or health monitoring systems. Used as energy harvesters, TENGs also provide a technological solution for powering wireless sensor networks (WSNs) nodes. As such, they enable self-powered systems that can integrate with storage technologies to extend their operational lifespan, in cases where other forms of energy are absent. Such application include the monitoring of structure health or industrial processes [1].

Triboelectric KEHs are usually direct-force systems, in which the external mechanical force is applied directly on one or both of the transducer's electrodes. This force alternatively separates and brings the two electrodes in contact. This contact leaves the surface of the dielectric material covering one or both electrodes with a nonzero average surface charge density, a process called *contact electrification*. This surface charge in turn induces charges on the transducer's electrodes conductive part, resulting in an electrostatic field that works against the mechanical force. In this way, energy is converted from the mechanical domain into the electrical domain. In addition to the charges induced by the charged dielectric, a component of the bias across the transducer is set and dynamically managed by the electrical circuit it is connected to. This circuit is called the *electrical conditioning circuit*. The power that is ultimately converted by an e-KEH is a function of the the conditioning circuit architecture, in addition to parameters such as the transducer's materials, the external force profile, or the transducer geometry.

To maximize the power converted by a triboelectric KEH, it is therefore crucial to carefully select this electrical conditioning circuit. A specific family of conditioning circuits, called *unstable charge-pumps* (UCPs), has drawn particular attention as they are able to boost the bias across the transducer to levels that are not limited by the bias resulting from the contact electrification effect [2]. Furthermore, UCPs do not require active synchronization with the transducer capacitance variation, as opposed to, e.g., synchronized electric charge extraction circuits [3].

Among UCPs, two commonly used subfamilies are the Low Capacitance Variation Rectifiers (LCVR) and the Cas-

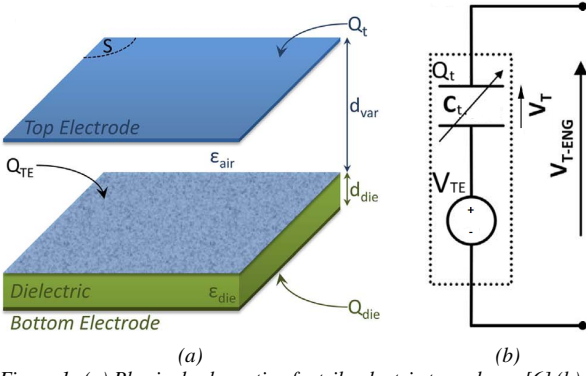


Figure 1: (a) Physical schematic of a triboelectric transducer [6] (b) Corresponding equivalent electrical model [6]

cade Bennet Doubler Rectifiers (CBDR). Each has its advantages depending on the triboelectric transducer's characteristics and the application context. Recently, Ambia *et al.* demonstrated that the LCVR architecture is optimal for systems without (semi-)permanent DC bias [4], which typically include electret-less MEMS-based KEH [5]. However, triboelectric KEH systems exhibit such a semi-permanent bias, and thus require a more general analysis.

In this study, we provide this analysis, deriving a criterion for selecting the best UCP architecture based on the system's capacitance ratio, bias voltage, and parasitic capacitance.

UNSTABLE CHARGE PUMPS

Single-dielectric TENGs (Fig. 1a) can be modeled as an electrical dipole comprised of the transducer's variable capacitor C_t in series with a DC voltage source of value V_{TE} (Fig. 1b). This DC source models the effect bias from the charges embedded in the dielectric material (Fig. 3) [6]. In the following, we restrict ourselves to transducer polarities such that $V_{TE} \leq 0$, which is the most advantageous case for energy harvesting. As the TENG is subjected to a mechanical excitation, the electrodes move relatively to each other. This results in the TENG capacitance varying periodically¹ between extreme values C_{min} and C_{max} . The voltage across the TENG is denoted by V_{TENG} . The voltage across C_t is denoted by V_T .

The energy converted in one cycle of capacitance variation is proportional to the enclosed area of the $Q_T - V_T$ cycle (Fig. 2). The unstable charge-pump circuits (UCPs) are a type of conditioning circuits for electrostatic transducers. They are made by special arrangements of diode and fixed capacitors. The UCP circuits can be characterized by two features of their $Q_T - V_T$ cycle, which translate into how they polarize the TENG throughout C_t 's variation:

- the parametric curve in the $Q_T - V_T$ plane of an UCP while it biases a periodically actuated transducer is a rectangle. This is shown in Fig. 2a. This holds in the absence of a significant parasitic capacitance (with respect to the transducer minimum capacitance C_{min}). If a parasitic capacitance C_p is present in parallel to

¹In fact, the variation needs not to be periodic as long as the local minima and maxima in time remain equal to C_{min} and C_{max} , respectively. Hence in the following, we use the terms "cyclic" and "periodic" variation interchangeably

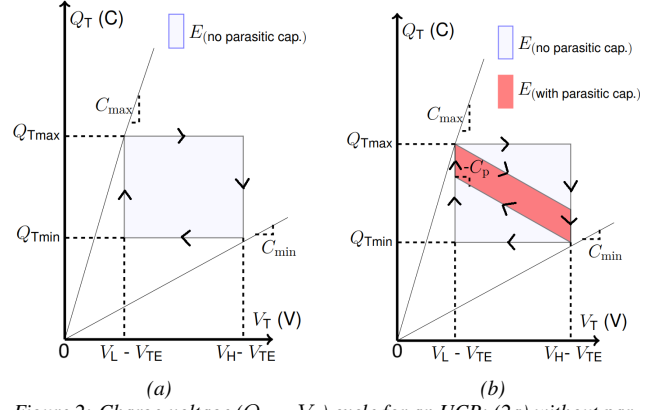


Figure 2: Charge-voltage ($Q_T - V_T$) cycle for an UCP: (2a) without parasitic capacitance and (2b) with parasitic capacitance. The arrows show the evolution direction during C_t variation.

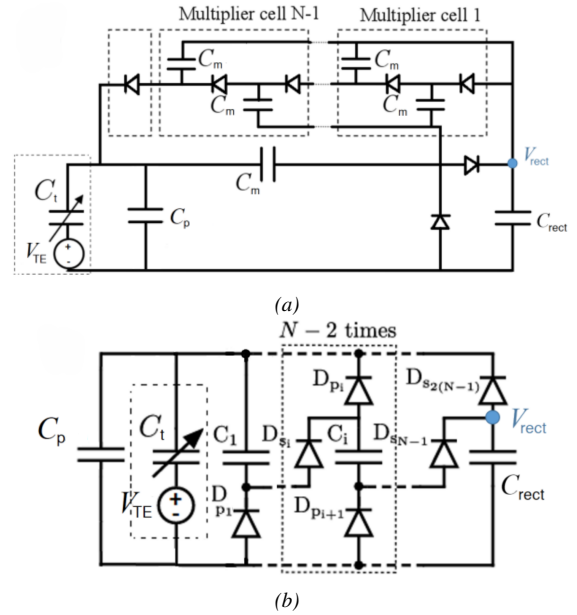


Figure 3: (a) Low Capacitance Variation Rectifier (LCVR) circuit [7] (b) Cascade Bennet Doubler Rectifier (CBDR) circuit [8].

the TENG dipole (due to, e.g., the conditioning circuit's capacitance, or to the experimental setup), then this cycle is modified into a parallelogram with two vertical sides, as in Fig. 2b.

- the ratio $\gamma := V_H/V_L$ is constant across all cycles in steady-state operation, where V_H and V_L denote the maximum and minimum voltage imposed by the conditioning circuit across the transducer.

One can show that the second point above implies that the capacitance variation ratio $\eta := C_{max}/C_{min}$ should exceed γ for the circuit to operate in the described steady-state mode. For any UCP circuit topology, if $\eta \leq \gamma$, then the steady-state operation mode is degenerated and no energy is converted. Since the converted energy is reinvested into the capacitors of the UCP, another consequence of the points above is that the non-degenerated steady-state operation mode exhibits an exponential increase of the voltages across the circuit's capacitors and across the transducer (hence the term *unstable*), cycle after cycle. This is why such circuits allow to decorrelate the converted power levels by the TENG from the triboelectric voltage V_{TE} .

The two circuit families we focus on (LCVR and

CBDR) differ in the range of values they can implement for γ . The LCVR's generic topology is depicted in Fig. 3a. It implements γ of the form $\gamma = (N + 1)/N$, where N is the number of multiplier cells (so that $1 < \gamma \leq 2$). The CBDR topology, on the other hand, is depicted in Fig. 3b. By choosing the right number of parallel capacitance branches and their values, it can implement any ratio $\gamma \geq 2$.

OPTIMAL CHARGE-PUMP

In this section, we derive the value of γ that maximizes the converted energy under the constraints posed by the application: the transducer capacitance variation η , the built-in bias voltage V_{TE} , the maximum supported voltage V_{max} , and the parasitic capacitance value C_p . Table 1 summarizes notations used in the following.

Quantity	Symbol/definition
Variable capacitance in the TENG model	C_t
Minimum of C_t in a cycle	C_{min}
Maximum C_t in a cycle	C_{max}
Capacitance variation ratio	$\eta := C_{max}/C_{min}$
Parallel parasitic capacitance	C_p
Relative parasitic capacitance	$\beta := C_p/C_{min}$
Voltage across TENG terminals	V_{TENG}
Minimum of V_{TENG} in cycle	V_L
Maximum of V_{TENG} in cycle	V_H
Triboelectric voltage in the TENG model	$V_{TE} \leq 0$
Voltage across C_t of the TENG's model	V_T
Max. supported voltage at transducer terminals	V_{max}
Ratio of triboelectric and max supported voltage	$\nu := V_{TE}/V_{max}$
UCP voltage ratio	$\gamma := V_H/V_L$

Table 1: Notations and definitions

In the following, it is assumed that the parasitic capacitance C_p in parallel with the device does not have a voltage dependency. This simplifying assumption is not necessarily verified in practice. Indeed, a typical Si diode parasitic capacitance depends on the applied voltage. Therefore, the parasitic capacitance depends at least on the phase in the period, i.e., whether C_t is increasing to C_{max} or decreasing to C_{min} . As a result, the slopes of the non-vertical lines in the diagram of Fig. 2b are not necessarily equal (unlike what is represented). We however keep a single C_p value, independent of voltage and C_t variation phase, in order to simplify the following analysis. The effect of C_p remain qualitatively unchanged from this simplification.

The harvested energy per cycle corresponds to the area of the $Q_T - V_T$ cycle in Fig. 2b, which yields the expression

$$E = (V_H - V_L)(C_{max}(V_L - V_{TE}) - C_{min}(V_H - V_{TE}) - C_p(V_H - V_L)). \quad (1)$$

Restricting to UCP, V_L and V_H are additionally constrained by the relation $V_H = \gamma V_L$, as explained above.

This expression shows that, if no other constraint is considered, the value of E can reach arbitrarily high levels by the right choice of γ and V_L for example. As the available UCPs (LCVR and CBDR) allow to implement a wide range of γ , and as any V_L can be reached thanks to the unstable property of UCPs, arbitrarily high converted energy per cycle are not ruled out. Yet, this is obviously an unphysical situation. Therefore, additional constraints need to be taken into account in order to set a physical limit to the energy conversion process.

One such constraint stems from the fact that the maximum allowable voltage across the UCP or the TENG is typically limited. This is because (i) the dielectric material of the TENG is subject to breakdown for high values (ii) the components of the UCPs (diodes and capacitors) are subjected to the same phenomenon (iii) an additional power management unit is required in practice [9], which requires a switch with maximum voltage ratings.

The constraint that we are going to consider in the following is that of a maximum allowable voltage across the transducer terminals, i.e., we require that $V_{TENG} \leq V_{max}$. In the following, we define $\nu := V_{TE}/V_{max}$.

By remarking that E with $V_H = \gamma V_L$ and $V_H = V_{max}$ is an increasing function of V_{max} , we get the optimum ratio γ_{opt} under the voltage constraint by solving

$$\frac{dE}{d\gamma} = 0 \quad (2)$$

under these two equality constraints, which yields

$$\gamma_{opt} = \frac{2(\eta + \beta)}{2\beta + \eta + 1 - \nu(\eta - 1)}. \quad (3)$$

Additionally, to ensure operation in unstable mode (needed to have fixed γ ratio between V_H/V_L and to reach $V_{TENG} = V_{max}$ in the steady-state), we must ensure that $\eta > \gamma_{opt}$. This condition is always fulfilled for γ_{opt} in (3) if $\nu \leq 1$, which we will consider as verified.

We illustrate this result in Fig. 4. The black dashed line at $\gamma = 2$ shows the limit between the optimal choices of UCP: LCVR should be chosen for γ_{opt} under it, CBDR should be chosen for γ_{opt} above it. For systems with low capacitance variation and bias voltage, the LCVR architecture results in the largest converted energy per cycle. In particular, when V_{TE} is zero, LCVR should always be selected, in accordance with what was found in [4]. For systems with higher capacitance variation or larger bias voltages, the CBDR architecture becomes optimal. The results also demonstrates how the parasitic capacitance is a critical factor in the choice of the right conditioning circuit. This warrants further studies on the trade off between diodes voltage ratings and junction capacitances in the UCP design.

CONCLUSION

This study presents a novel criterion for selecting the optimal conditioning circuit for triboelectric nanogenerators. By comparing the performance of LCVR and CBDR circuits, we provide a practical method for maximizing the energy harvested per cycle based on the system's capacitance variation ratio, triboelectric voltage, parasitic capacitance,

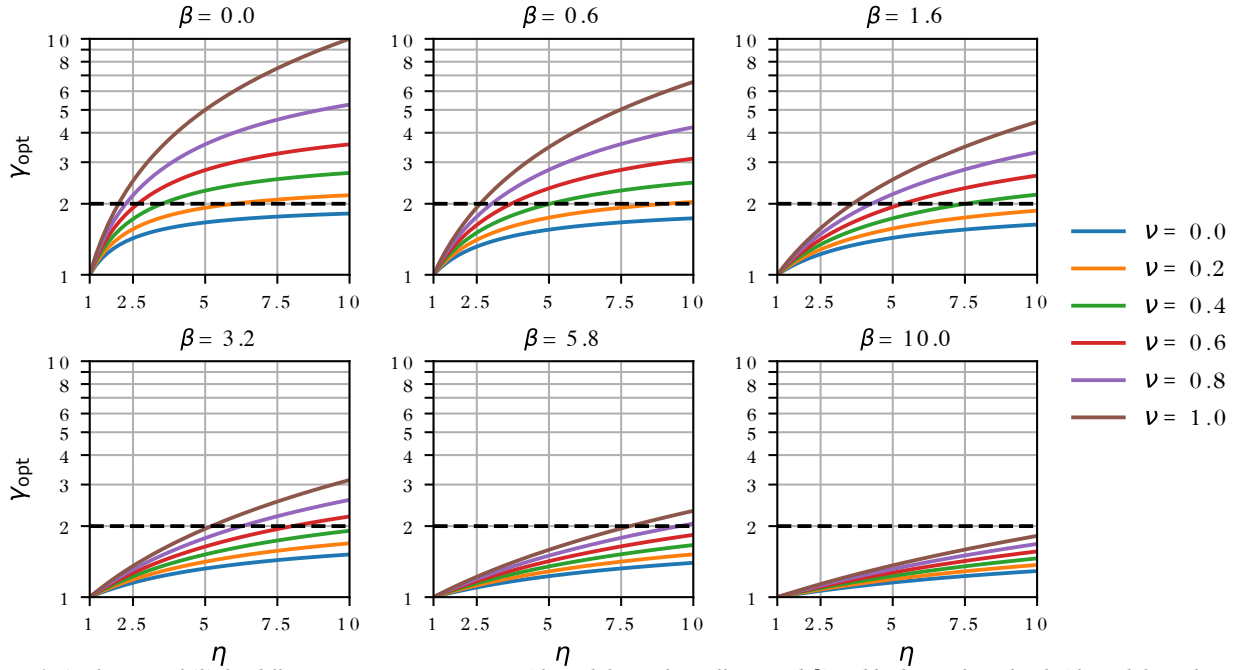


Figure 4: Application of (3) for different parasitic capacitances (through logarithmically-spaced β) and built-in voltage levels (through linearly-spaced ν). The black-dashed line $\gamma = 2$ represents the limit between achievable γ_{opt} using LCVR UCP topology ($\gamma_{\text{opt}} \leq 2$) and CBDR UCP topology ($\gamma_{\text{opt}} \geq 2$).

and maximum supported voltage. The results demonstrate that while the LCVR topology is optimal for low built-in voltage transducers of low capacitance variation, the CBDR topology should be selected for larger, higher built-in voltage systems. These insights will aid in the development of more efficient triboelectric nanogenerator systems for kinetic energy harvesting applications. Future works could seek to experimentally demonstrate these findings, or to push the optimization to account for the dependency of the parasitic capacitance to each UCP topology. Another important study is the implications of voltage constraints across pairs of terminals of the circuit, other than the transducer terminals.

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